# THE EFFECT OF ORGANOMINERAL FERTILIZER PHOSPHORUS ON THE AVAILABILITY OF PHOSPHORUS IN A CALCAREOUS SOIL

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**Abstract.** This study focused on the effect of organomineral fertilizers on phosphorus availability and uptake by plants in calcareous soils. With this aim, an incubation test and a pot experiment were carried out to see the effect of phosphorus in the organomineral fertilizer prepared by mixing the mineral fertilizer source phosphorus with the organic fertilizer from the biogas plant on the availability of phosphorus in soil and on the nutrition of the wheat plant. In both experiments, increasing rates of organomineral fertilizer-phosphorus were applied, and they were compared with the triple superphosphate. The soils were sampled twice in the incubation experiment. In the pot experiment, two samples were taken in the tillering and maturation periods. Within the tillering period, the whole plant was sampled, and two separate samples, namely stover and grain, were taken at maturity. The results of the incubation experiment showed that the contents of Olsen-phosphorus in the soils treated with organomineral fertilizer-phosphorus were higher than those with mineral fertilizer-phosphorus. In line with this, both the phosphorus concentration in the shoots and the phosphorus uptake per pot were higher in the plants treated with the organomineral fertilizer-phosphorus in the tillering period. A similar trend was observed for phosphorus content in grains and total phosphorus uptake at maturity.
**Keywords:** *biogas plant compost, nutrient uptake, organomineral fertilizer, phosphorus, wheat*

## Introduction

The predicted growth in the human population implies that the need for food security and healthy nutrition of an increasing number of people must be met. It is estimated that the demand for food will increase by 70% with the current consumption habits (Bruinsma, 2009). While this surge requires more agricultural production, we must achieve increased production in limited areas under the threat of global climate change and variability, the adverse effects of which are already being seen. The increasing population, declining rural population, increases in income levels, and changes in the rate of poverty in society over time constitute the main socio-economic factors that lead to increased food demand considering future world food consumption (Erenoğlu and Hacırüstemoğlu, 2022). In addition to these, when the production contractions and fluctuations that will be potentially faced because of global warming are added, it is clear that an overly complex set of problems awaits human beings.

The global population growth increases the demand for agricultural production leading to a rising dependence on fertilizer inputs (Kominko et al., 2017) which require energy for their production. For this reason, both increasing plant yield and minimizing possible environmental risks due to plant nutrients are among the primary goals of the present plant nutrition activities. Using MFs in crop production supports the fertility of soils chemically, but more is needed to improve its physical and biological properties, especially in shallow areas of organic matter. For this reason, these soils should mainly


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be supported with organic matter. Although soil organic matter constitutes a meager percentage of soils, it is a crucial soil component that affects soil fertility and structure in agriculture. Humus covers the clay minerals in the soil, thus preventing the clay minerals from bonding to each other and increasing the exchange capacity of these molecules. The high cation exchange capacity of humus provides better use of chemical fertilizers by the plant. It prevents them from moving away from the root zone, combining with high-valent cations such as iron ($Fe^{3+}$), copper ($Cu^{2+}$), and zinc ($Zn^{2+}$) to form chelates and loading these cations. As a result, humus neutralizes them and facilitates their uptake by plants. In addition, it increases the activities of microorganisms in the soil. For these reasons, research on applying organic matter to soil, especially in areas with low organic matter, and the effects of humus resources on plant growth and soil properties have gained momentum in recent years.

Animal manure and MFs have been widely used to supply macro-and micronutrients in plant production for a long time. In addition, many materials, such as food, sewage, and other industrial wastes, are used to produce OMFs (Chassapis and Roulia, 2008; Rady, 2012; Kominko et al., 2017). Applying MFs together with organic improvers has a dual effect that enhances crop yield and recycles agricultural waste (Lekfeldt et al., 2017; Yadav et al., 2019; Erenoğlu and Hacırüstemoğlu, 2022). Best nutrient management practices preferably consist of manure, harvest rests, and MF to supply crop nutrient requirements (Ju and Zhang, 2021). Therefore, the fertilizer industry has also focused on producing organomineral fertilizers, which are obtained from the mixture of organic residues, such as biogas plants or wastewater sludge treatment plants, with mineral fertilizers.

Using natural OFs and OMFs is one of the most critical issues of sustainable agricultural practices. Organic fertilizers can differ since natural fertilizers have distinct degrees of decomposition; they break down and decompose slowly. Therefore, their nutrient distribution varies depending on the source material. On the other hand, OMFs contain plant nutrients found in chemical fertilizers and organic matter simultaneously so that nutrients can be presented in a more standardized form in terms of content (Smith et al., 2020). In organomineral fertilizers, plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and organic matter originating from humic-fulvic acid, compost or leonardite are used together as a base fertilizer. It is thought that OMFs produced as "organic matter + mineral fertilizer" by utilizing the positive effects of organic materials on soil fertility, on the one hand, and reducing the loss of nutrients by leaching, on the other hand, increase the efficiency of the mineral nutrients used by improving the fertility of the soil in the rhizosphere (Smith et al., 2020).

Application of manure-based organic fertilizer or humic substances can affect plant P uptake in two ways: i) increasing its mobility and recovery (Delgado et el., 2002; Shafi et al., 2020; Zhang et al., 2022) and ii) allowing it to be transported to longer distances (Du et al., 2013; Erenoğlu and Dündar, 2020).

Overusing P in plant production causes P accumulation in the soil and creates a risk in terms of P losses to the waterbodies (Rowe et al., 2016; Zhou et al., 2021). Since it is bound in the soil as adsorbed or Ca-P and Al/Fe-P precipitates depending on the soil pH and redox condition, most of the P applied in plant production converts to unavailable forms (Gu et al., 2020; Barrow et al., 2021; Zhang et al., 2021b). After that, the changes in soil properties altered by soil management can mobilize fixed P (Nobile et al., 2020). Therefore, understanding the conversion and mobilization of soil P under agricultural practices is highly important. Long-term application of organic ameliorates to soils affects


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organic matter content (Li et al., 2021). In addition, organic matter causes slight and microsite acidification in calcareous soils (Guo et al., 2018; Yan et al., 2018). Soil acidification increases the conversion of Ca–P into Al/Fe–P in different soils (Yang et al., 2015; Liu et al., 2017; Chen et al., 2018). Very recently, Zhang et al. (2022) showed high Ca-P transformation to Al/Fe-P in soils supplied with MF and manure and attributed this to the high proportion of humic-like substances in dissolved organic matter, which may have led to a slight/microsite acidification. In well-weathered soils in conditions of flooding or high rainfall, fortified labile OM content also can cause the change in soil P by inducing Fe(III) reduction (Maranguit et al., 2017; Khan et al., 2019) and in the microsites of well-drained oils (Warrinnier et al., 2020). In general, the mobilization of soil P induced by Fe(III) reduction is commonly coupled with decreasing soil Al/Fe-P content (Zhang et al., 2021a,b).

As a result of the change in the rhizosphere, better roots' growth can help use nutrients more effectively, especially those with limited mobility, such as P. In addition, it has been emphasized that humic substances in the applied organic material can reduce the fixation of P in the soil (Brady and Weil, 2017). In parallel with this, a study conducted in the calcareous soils of the Mediterranean Region showed that the application of humic-fulvic acid plays a vital role in the recovery of P in the soil (Delgado et al., 2002). In recent past, the enhancing effect of long-term organic amendment additions on P mobility in calcareous soil was clearly shown (Zhang et al., 2022).

Humin substances were influential not only on the availability and mobility of P in the soil but also on plant yields and P uptake by plants. For instance, Tahir et al. (2011) stated that humic acid application increased the P content of wheat grown in calcareous soils. Similarly, the applications of mineral P and HA at rising rates increased the agronomic responses of wheat under field conditions (Shafi et al., 2020). In another study conducted with a bread wheat cultivar under greenhouse conditions, the humic-fulvic acid (HA+FA) solution applied in liquid form did not affect wheat development or nutrient uptake (Erenoğlu and Dündar, 2020). However, in the same study, P movement was better in the disturbed soil column incubated with HA+FA than in soils without these. In parallel, Erenoğlu and Hacirüstemoğlu (2022) have shown that the organic fertilizer applied in combination with plant nutrients can increase the nutrient use efficiency of plants by improving the uptake of nutrients, especially P.

Because of the above-given reasons, the present manuscript was planned in two parts: i) an incubation experiment under laboratory conditions and ii) a pot experiment under greenhouse conditions. In the incubation experiment, available P change was observed in a calcareous soil incubated with varying OMF-P and MF-P rates for 45 and 90 days. The effects of OMF-P and MF-P applications at different rates on wheat plants' growth and P uptake were investigated in the pot experiment conducted under greenhouse conditions.

## Materials and methods

### *Experimental Soil and Plant Material*

In the study, Arık Series soil with low organic matter content, high pH (7.63), high calcium carbonate, and high clay content was used to stand for the soils of the Çukurova Region. The experimental soil contained 11.7 ppm (moderate) $NaHCO_3$ extractable P and 400 ppm (high) $NH_4$-acetate extractable K (Morsy Mohammed Morsy, 2022). After the soil was taken from the field, it was air-dried and passed through a 4 mm sieve. A bread


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wheat (*Triticum aestivum* L. cv. Adana-99) cultivar extensively cultivated in the region was used in the pot experiment.

### *Fertilizers*

In the studies, an organic fertilizer containing 53% OM, %20 HA+FA, 3% $P_2O_5$, 2% N, and 1% $K_2O$ originating from the biogas plant, triple superphosphate (TSP; 42% $P_2O_5$), urea (46% N), and potassium sulfate (50% $K_2O$) fertilizers were used. Organomineral fertilizer (OMF) containing 22.4% $P_2O_5$, total P, and 25% OM was produced under laboratory conditions by mixing organic fertilizer, TSP, and quartz sand as given in *Table 1*. While the TSP was used as an MF-P source (*Table 1*), potassium sulfate ($K_2SO_4$) was utilized as a K and S source. To ensure the homogeneous application of fertilizers, all fertilizing materials used in the study were ground through a blender.

***Table 1.*** *Raw materials used in the preparation of organomineral and mineral fertilizers, amounts of raw materials, and P and OM content in the final product*

| **P fertilizers** | **Raw materials and their amounts, %** | **Content, %** | |
|---|---|---|---|
| | | **P as $P_2O_5$** | **OM** |
| **Organomineral fertilizer (OMF)** | Organic fertilizer, 47.2<br>TSP, 42<br>Quartz sand, 2.8 | 22.4 | 25 |
| **Mineral fertilizer (MF)** | TSP, 100 | 42 | - |

### *Organomineral Fertilizers and Olsen-P in Soil (Incubation Experiment)*

This part of the study was conducted as an incubation experiment, 0, 25, 50, and 75 mg $P \cdot kg^{-1}$ soil rates were applied using OMF and MF. The incubation process occurred in containers containing 250 g of soil as three replicates (*Photo 1A*). The required amounts of fertilizers were applied for each rate. In addition, the N levels in all incubation containers were kept constant to end the possible effects of N on the activities of microorgnisms. Therefore, using urea, 150 mg $N \cdot kg^{-1}$ soil was added with other fertilizer materials. At the end of the 45- and 90-day incubation periods, the soils in the containers were homogenized, passed through a 2 mm sieve, and then subjected to $NaHCO_3$-Extraction (Olsen P analysis).

### *Organomineral Fertilizers and Phosphorus Nutrition (Pot Experiment)*

A pot experiment was conducted under greenhouse conditions to see the effect of P sources on the P uptake of wheat. As in the incubation experiment, four different rates (0, 25, 50, and 75 mg $P \cdot kg^{-1}$ soil) of P were applied using OMF and MF. The pots were filled with 3 kg of the experimental soil that was sieved through 5 mm sieves (*Photo 1B*). All the base fertilizer applications were made just before planting, 5 cm below the seedbed. To ensure the homogeneous application of fertilizers, all fertilizing materials used in the study were ground through a blender, as mentioned above. Half of the N, 75 mg $N \cdot kg^{-1}$ soil (as urea), and whole K, 100 mg $K \cdot kg^{-1}$ soil (as $K_2SO_4$), were applied as a starter fertilizer to the same area with P fertilizers. The rest of the N (75 mg $N \cdot kg^{-1}$) was applied after the harvest at tillering stage. The pots were regularly weighed and watered at 50% of the field capacity during the first week after planting, 80% in the following week, and at 100%, in the next period. Half of the experiments' pots, designed according to the


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randomized plot design with six replications, were harvested at the end of the tillering stage (Zedoks 29) 45 days after sowing.

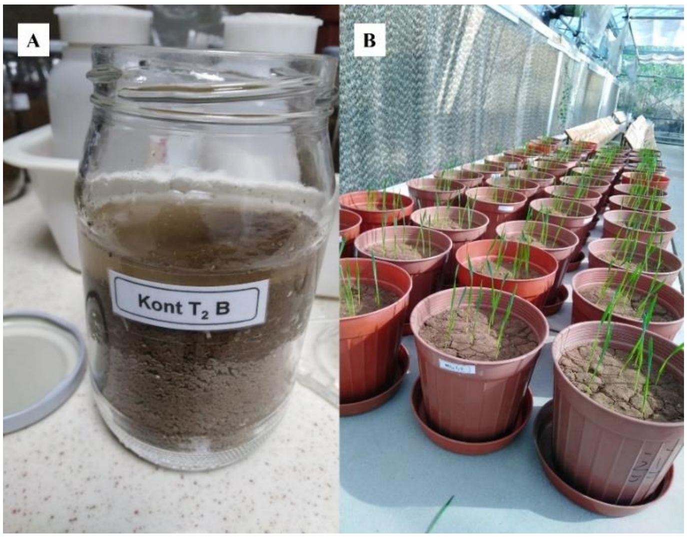


***Photo 1.*** *Views from Incubation Experiment (A) and Pot Experiment (B)*

In the experiment, visual observations were made, and two harvests at tillering (45 days later) and ripening (150 days later) stages were collected. At the end of the experimental period, the shoots and grains of wheat cultivar Adana-99 were harvested, and the biomass, grain yields, and nutrient uptakes were figured out.

The plants were harvested and dried in an oven at 65 °C for two days. After that, the dry weights of samples were taken and homogenized using a grinder. The homogenized samples were wet-ashed in a microwave oven. While their P contents were determined using UV-sisible spectrophotometry, K concentrations were determined using AAS. Nitrogen concentrations in samples were measured using the Kjeldahl method.

The grains and stover were sampled 150 days after sowing, and grain yields, dry weights, and nutrient concentrations were determined as described above for the shoot samples.

### *Statistical Analyses*

At the end of the study, all values obtained from the experiment were subjected to one-way ANOVA using the software "IBM SPSS Statistics Version 20". The significance levels of the treatments were determined. The averages of different applications in the measured parameters were compared with the Duncan Test at the probability level of $p \leq 0.05$. The averages that differed from each other are shown with different letters.

## Results

### *Organomineral Fertilizers and Olsen-P in Soil (Incubation Experiment)*

Sodium bicarbonate extractable P levels of the experimental soil incubated with increasing rates of P applied either as OMF or MF for 45- and 90 days are presented in *Figure 1*. As seen, at the end of the incubation period of 45 or 90 days, $NaHCO_3$-extractable P (Olsen P) levels in the soil increased linearly due to increasing P application


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in OMF or MF forms. At the end of the 45-day incubation period, there was a tendency that 25 and 50 mg·kg$^{-1}$ soil P rates of OMF application caused higher $NaHCO_3$-extractable P than MF, but this result was not statistically significant. In contrast, at the end of the 90 days, P supplies in the form of OMF at all P rates resulted in statistically significant increases in $NaHCO_3$-extractable P levels compared to MF.

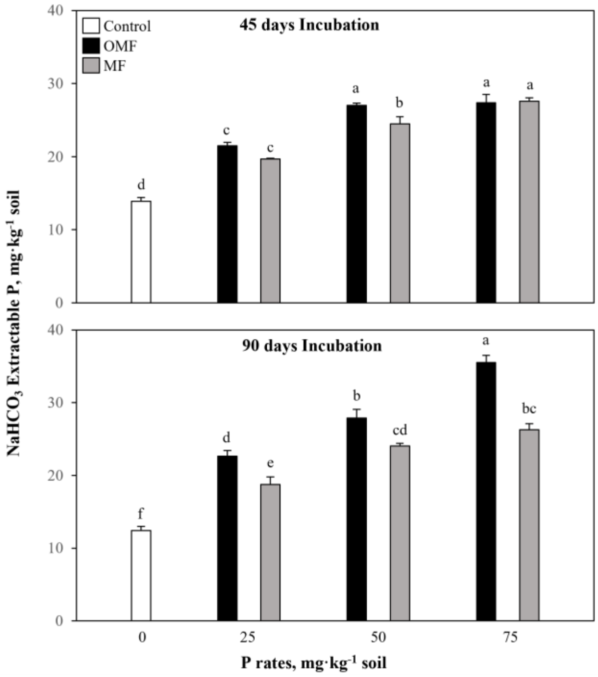


***Figure 1.*** *Sodium bicarbonate extractable P levels of the experimental soil incubated with increasing rates of P applied either as OMF or MF for 45- and 90 days. Values are the means of three independent replicates ± SE. Columns with different letters significantly differ for each trait at p ≤ 5%, according to ANOVA followed by Duncan's test*

## *Organomineral Fertilizers and Phosphorus Nutrition (Pot Experiment)*

### *Plant Growth and Grain Yield*

Tillering: *Figure 2* shows the shoot dry weights of wheat plants harvested at the end of the tillering stage, 45 days after sowing. The P application increased the shoot dry weight irrespective of fertilizer type. In addition, the plants supplied with OMF-P had better shoot growth at 25 and 50 mg P·kg$^{-1}$ soil than those fertilized with MF (*Figure 2*), and these differences were statistically significant. However, in the case of the highest P rate, although OMF-P showed a trend of increasing shoot growth, the effect was not statistically significant.

Ripening: *Figure 3* presents the dry weights of stover (shoot + husks - A) and grains (B) of wheat plants harvested 150 days after sowing. As can be seen, when the dry weights of the stover were considered, it was determined that the shoot dry weights of plants increased with the P application compared to the control plants. However, the difference became smaller (*Figure 3A*) as contrasted with the 45 days old plants (*Figure 2*).


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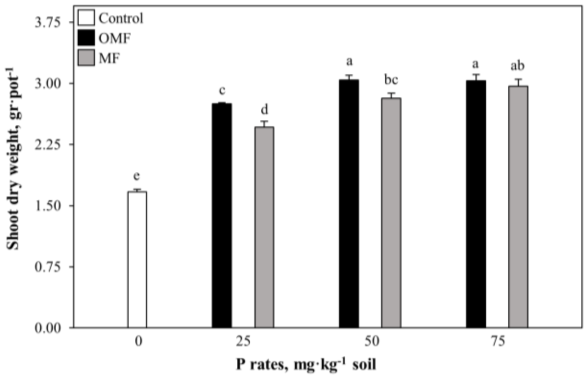


***Figure 2.*** *Shoot dry weights of wheat grown with increasing rates of P applied as either OMF or MF for 45 days in the experimental soil under greenhouse conditions. Values are the means of three independent replicates ± SE. Columns with different letters significantly differ at $p \leq 5\%$, according to ANOVA followed by Duncan's test*

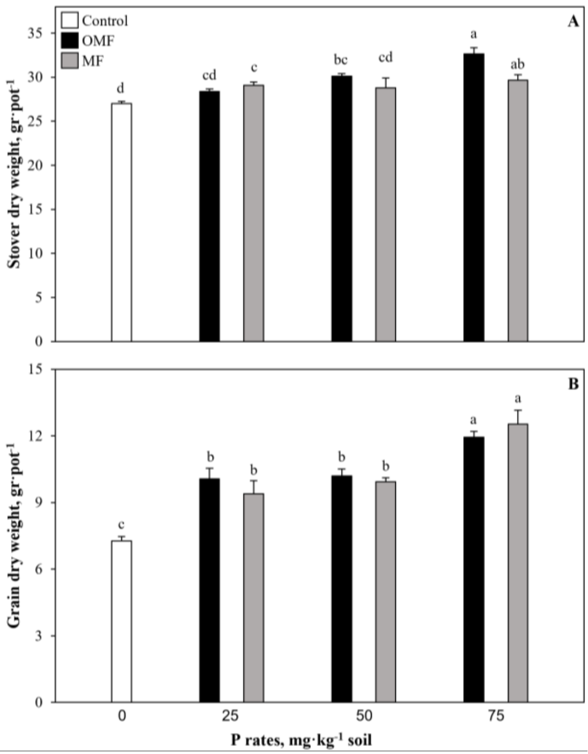


***Figure 3.*** *Dry weights of stover (A) and grains (B) of wheat grown with increasing rates of P applied as either OMF or MF for 150 days in the experimental soil under greenhouse conditions. Values are the means of three independent replicates ± SE. Columns with different letters significantly differ for each trait at $p \leq 5\%$, according to ANOVA followed by Duncan's test*

On the other hand, it was observed that the difference increased even more notably in the case of grain dry weights (*Figure 3B*). Although, it seemed that there was still a boosting effect of OMF-P on the grain dry weight of the plants supplied with 25 or 50 mg $P \cdot kg^{-1}$ soil in parallel with the shoot dry weights noted for the plants harvested 45 days after sowing, the difference was statistically not significant.


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*Phosphorus Nutrition of Plants*

Tillering: *Figure 4* poses the P concentrations in shoots (A) and P uptake (B) of 45 days old wheat plants. Regardless of the fertilizer types, P application increased the P concentrations in the shoot. The OMF-P-applied plants showed higher P concentrations at all P levels than the MF-P-used plants (*Figure 4A*). However, the effect was statistically insignificant at the high P levels. In addition, these differences were statistically significant at 25 mg P·kg$^{-1}$ soil and became more apparent as the P rate decreased.

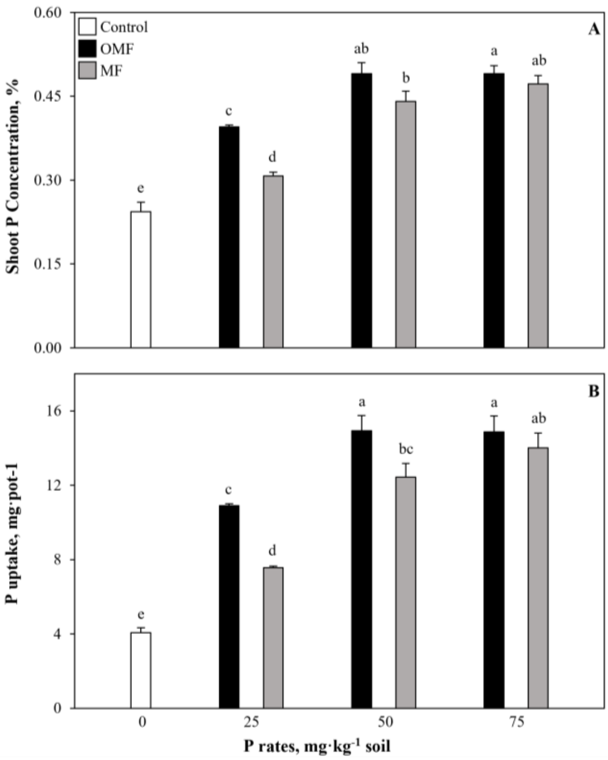


***Figure 4.** Shoot P concentration (A) and P uptake (B) of wheat grown with increasing rates of P applied as either OMF or MF for 45 days in the experimental soil under greenhouse conditions. Values are the means of three independent replicates ± SE. Columns with different letters significantly differ for each trait at p ≤ 5%, according to ANOVA followed by Duncan's test*

When the P uptake values calculated by multiplying the P concentrations in the shoots with the dry weights were evaluated, it was seen that the OMF-P applications increased the total P uptake compared to the MF-P (*Figure 4B*). Furthermore, parallel to the P concentrations, these relations were statistically significant at 25 and 50 mg P·kg$^{-1}$ soil, and the power of importance was enhanced with the decrease in the level of applied P (*Figure 4B*).

Ripening: As shown in *Figure 5A*, P concentration in stover increased with rising P application rates. However, different fertilizer application forms did not cause any difference in P concentrations of the harvest rests (*Figure 5A*). However, unlike P concentrations in shoots and stover, P application did not significantly affect the P concentrations of grains (*Figure 5B*).


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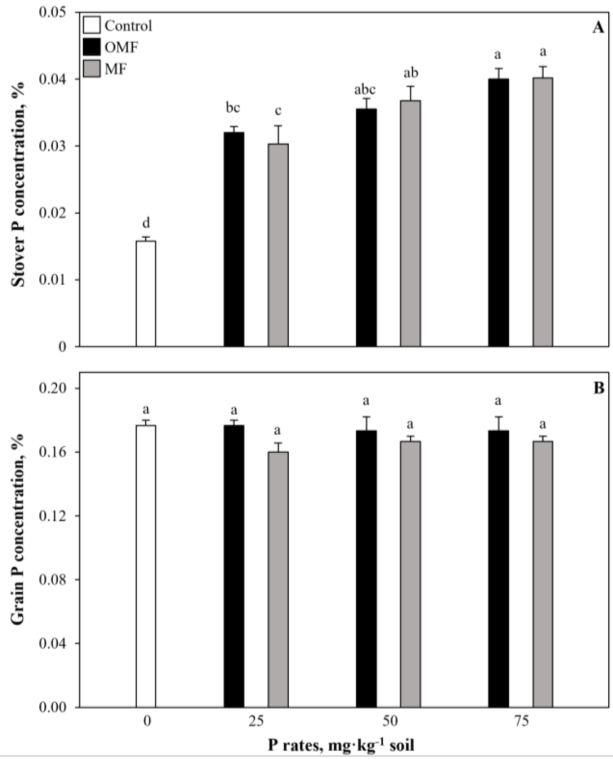


***Figure 5.*** *Phosphorus concentration in stover (A) and grains (B) of plants grown with increasing rates of P applied as either OMF or MF for 150 days in the experimental soil under greenhouse conditions. Columns with different letters significantly differ for each trait at $p \leq 5\%$, according to ANOVA followed by Duncan's test*

*Figures 6 A,B*, and *C* show the P contents of stover and grains, and the P uptakes obtained by their summing. As illustrated, the P application had an increasing effect on all three traits. Moreover, the P contents of grains were higher than those of the stovers. Regarding the P content of stovers, although OMF-P-applied plants tended to have higher P contents than MF-applied ones for all three P rates, the differences were statistically insignificant (*Figure 6A*). Regarding the P content of grains, it was clear that the OMF-P application provoked higher P contents than the MF application except for the highest P level (*Figure 6B*). However, the increasing effect of OMF-P was statistically not significant at 50 mg P·kg$^{-1}$ soil level. Consistent with the P content in the grains, there was a substantial relationship between the total P uptake of the plants and the forms of P fertilizer, especially in low P applications (*Figure 6C*). In such manner, for all three phosphorus rates, the plants supplied with OMF-P had higher total P uptake than the plants of MF-P application, and when it dropped to 25 mg P·kg$^{-1}$ soil, the difference became statistically significant.

### *Nitrogen and Potassium Nutrition of Plants*

Tillering: *Table 2* shows the N and K concentrations of the shoots and their uptake in the 45 days old wheat plants. Increasing P application in OMF and MF forms enhanced N concentrations in the shoot but did not affect K concentrations. The N concentrations in the shoot of wheat plants fertilized with P in the mineral form were higher than those fertilized with P in the OMF-P form, contrary to the P concentrations of the same plants.


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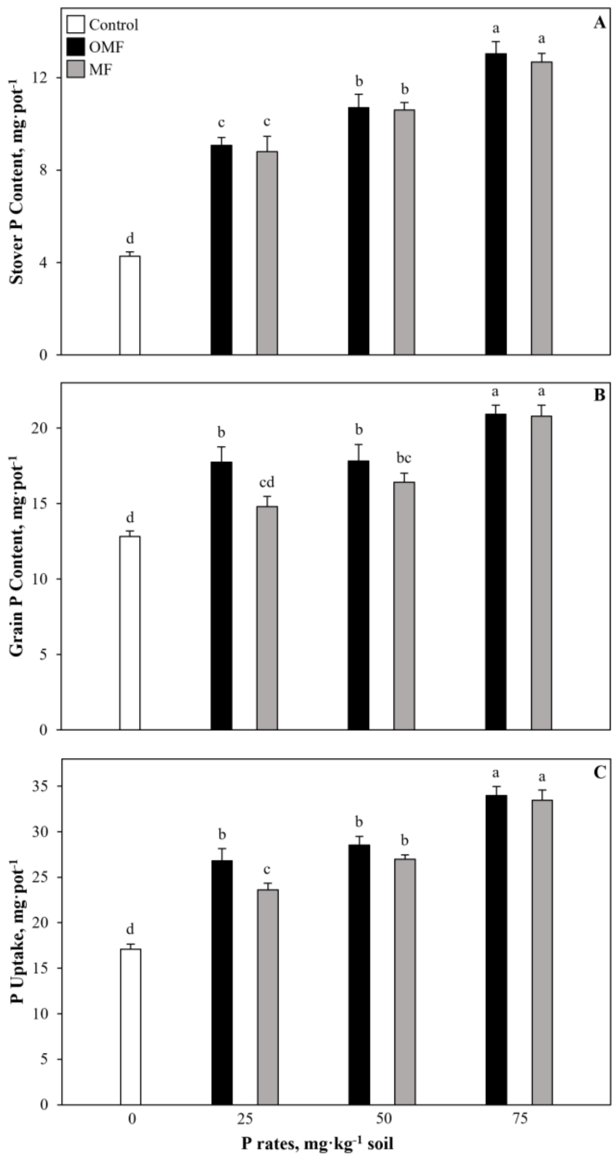


***Figure 6.*** *Phosphorus content of stover (A) and grains (B) and total P uptake (C) of plants grown with increasing rates of P applied as either OMF or MF for 150 days in the experimental soil under greenhouse conditions. Columns with different letters significantly differ for each trait at $p \leq 5\%$, according to ANOVA followed by Duncan's test*

At the same time, there have been more net increases in the N and K uptake; the N and K uptakes of the plants broadened with an increment in P rates irrespective of the application form (*Table 2*).

Ripening: *Table 3* presents the N and K concentrations in the stover, and grains of wheat grown for 150 days. In general, while the N concentrations in the stover were lower than those of the grains, it was the opposite for K. None of the N or K concentrations in the stover or grains) changed in relation to the P fertilizer's increased P rate or form (*Table 3*).

Irrespective of application forms, the P application positively affected the total uptakes of both N and K (*Table 4*). However, there was no statistically significant relationship between the P fertilizer form and the uptake of neither N nor K (*Table 4*).


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***Table 2.** Nitrogen and K concentrations in shoots and uptakes of wheat grown with increasing rates of P applied as either OMF or MF for 45 days in the experimental soil under greenhouse conditions. Average values ± SE with different letters differ significantly for each trait, at p ≤ 5% according to ANOVA followed by Duncan's test*

| Fertilizer Source | P rates mg·kg⁻¹ soil | Concentration, % | | Uptake, mg·pot⁻¹ | |
|---|---|---|---|---|---|
| | | N | K | N | K |
| **Control** | **0** | 2.88 ± 0.01 c | 6.96 ± 0.20 bc | 48 ± 2 c | 116 ± 5 c |
| **OMF** | **25** | 3.51 ± 0.03 b | 7.38 ± 0.08 a | 97 ± 2 b | 203 ± 3 a |
| | **50** | 3.84 ± 0.01 ab | 6.81 ± 0.17 c | 117 ± 7 a | 207 ± 1 a |
| | **75** | 3.86 ± 0.01 ab | 6.95 ± 0.09 bc | 117 ± 6 a | 210 ± 6 a |
| **MF** | **25** | 3.83 ± 0.02 ab | 7.28 ± 0.11 ab | 94 ± 7 b | 180 ± 8 b |
| | **50** | 4.07 ± 0.02 a | 7.11 ± 0.04 abc | 115 ± 6 a | 200 ± 4 a |
| | **75** | 4.27 ± 0.04 a | 6.82 ± 0.11 c | 125 ± 3 a | 202 ± 8 a |

***Table 3.** Nitrogen and K concentrations of stover and grains of wheat grown with increasing rates of P applied as either OMF or MF for 150 days in the experimental soil under greenhouse conditions. Average values ± SE with different letters differ significantly for each trait, at p ≤ 5% according to ANOVA followed by Duncan's test*

| Fertilizer Source | P rates mg·kg⁻¹ soil | Concentration, % | | | |
|---|---|---|---|---|---|
| | | N | K | N | K |
| | | STOVER | | GRAIN | |
| **Control** | **0** | 0.46 ± 0.01 bc | 3.18 ± 0.26 a | 2.50 ± 0.2 ab | 0.52 ± 0.01 a |
| **OMF** | **25** | 0.55 ± 0.03 a | 3.09 ± 0.13 a | 2.59 ± 0.08 a | 0.45 ± 0.03 b |
| | **50** | 0.48 ± 0.01 abc | 2.87 ± 0.19 a | 2.38 ± 0.04 ab | 0.51 ± 0.02 ab |
| | **75** | 0.44 ± 0.01 c | 2.90 ± 0.06 a | 2.29 ± 0.02 ab | 0.49 ± 0.03 ab |
| **MF** | **25** | 0.55 ± 0.02 a | 3.28 ± 0.10 a | 2.33 ± 0.09 ab | 0.52 ± 0.01 a |
| | **50** | 0.53 ± 0.02 ab | 3.24 ± 0.21 a | 2.33 ± 0.10 ab | 0.54 ± 0.03 a |
| | **75** | 0.49 ± 0.04 abc | 2.96 ± 0.14 a | 2.22 ± 0.08 b | 0.54 ± 0.00 a |

***Table 4.** Total N and K uptake (E-F) in wheat grown with increasing rates of P applied as either OMF or MF for 150 days in the experimental soil under greenhouse conditions. Average values ± SE with different letters differ significantly for each trait, at p ≤ 5% according to ANOVA followed by Duncan's test*

| Fertilizer Source | P rates mg·kg⁻¹ soil | Uptake*, mg·pot⁻¹ | |
|---|---|---|---|
| | | N | K |
| **Control** | **0** | 308 ± 16 c | 897 ± 66 a |
| **OMF** | **25** | 418 ± 15 ab | 924 ± 45 a |
| | **50** | 386 ± 5 b | 919 ± 53 a |
| | **75** | 418 ± 6 ab | 1006 ± 40 a |
| **MF** | **25** | 381 ± 14 b | 1004 ± 31 a |
| | **50** | 385 ± 2 b | 991 ± 91 a |
| | **75** | 432 ± 12 a | 998 ± 27 a |

*Sum of nutrients in stover and seed (mg·pot⁻¹)


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## Discussion

### *The Effect of OMF-P on P Availability/Mobility in Soils*

Application of manure-based organic fertilizer or humic substances can affect plant P uptake in two ways: i) increasing its mobility and recovery (Delgado et al., 2002; Shafi et al., 2020; Zhang et al., 2022) and ii) allowing it to be transported to longer distances (Du et al., 2013; Erenoğlu and Dündar, 2020).

The current study found that compared to mineral P, the incubation of organomineral P caused higher $NaHCO_3$ extractable plant-available P in the experimental soil at the end of the 45- and 90-day incubation period (*Figure 1*). It was recently shown that long-term organic amendments enhanced P mobility and reduced P adsorption in calcareous (Farid et al., 2021; Zhang et al., 2022) and non-calcareous soil (Farid et al., 2021). These findings agree with the results found by Delgado et al. (2002). In their study, they revealed that the application of humic-fulvic acid plays a significant role in the recovery of P in the calcareous soils of the Mediterranean Region (Delgado et al., 2002). In the current study, the reason for the higher plant-available Olsen P in the soil incubated with organomineral fertilizer P than the mineral fertilizer may also be the humic substances from the organic raw material (*Figure 1*). Slight and microsite acidification in calcareous soils (Guo et al., 2018; Yan et al., 2018) due to humic-like substances (Zhang et al., 2022) around mineral P sources might be one of the possible reasons for enhanced Olsen P levels (*Figure 1*). An additional reason may be the increased mobilization of soil P due to Fe(III) reduction in micro-sites and the decrease in soil Al/Fe-P contents (Zhang et al., 2021a,b). Moreover, humic substances can enhance P availability by increasing the distance of P movement (Du et al., 2013; Erenoğlu and Dündar, 2020) and the concentration of extractable P in soil (Du et al., 2013; Shafi et al., 2020). While Du et al. (2013) showed increased P movement in the nearby soil volume surrounding the fertilizer granule, Erenoğlu and Dündar (2020) were also able to detect P in soil solution samples taken at a vertical distance of 15 cm from the application point when P was applied in the liquid form. However, in the case of granular fertilizer application, P was detectable in soil solution samples taken 5 cm below the application point (Erenoğlu and Dündar, 2020).

### *The Effect of OMF-P on Shoot Growth and Grain Yield of Wheat*

Forty-five days after sowing, the application of OMF-P caused significantly higher shoot growth than the MF-P application at each P level from 25 to 75 mg $P \cdot kg^{-1}$ soil (*Figure 2*). There was good accordance between shoot growth (*Figure 2*) and $NaHCO_3$ extractable P in soils incubated with OMF-P or MF-P for 45 days (*Figure 1*). When stover dry weights for the final harvest are taken into consideration, although it is statistically not significant, it is seen that the plants fertilized with OMF at higher P rates had more stover than those fertilized with MF (*Figure 3A*). Regarding grain dry weight, although the grain yields in the pots fertilized with OMF in the lowest two P treatments were higher than those treated with MF, this difference was not statistically significant (*Figure 3B*). The current study was conducted in a limited volume in the pot, and the significant differences in favour of plants fertilized with OMF in the initial period may have disappeared in the later periods as the roots reached the entire pot. Therefore, it was essential to compare the subjects in this study in larger pots and/or field conditions. Recently, our research group started a two-year study to see the effect of OMF-P on the agronomic responses of wheat grown in rainfed and irrigated conditions. First-year results


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have shown that under irrigated conditions OMF-P application increased the agronomic effect of P in comparison to MF-P application (Erenoğlu et al., manuscript in preparation). The present results are also consistent with previous studies stating that using organic fertilizers will result in better plant growth than the use of only mineral fertilizers, apart from the additional organic matter input to the soil (Steiner et al., 2007; Ayinla et al., 2018). However, the soils of both experimental sites were low in soil fertility and cation exchange capacity (CEC); they were highly weathered clayey and sandy soil, respectively. In a study conducted with sweet corn in clayey loam soil, Canatoy and Daquiado (2021) demonstrated that vermicompost application and mineral NPK increased the canopy and grain yields. In a recent study conducted under greenhouse conditions, the application of fixed rates of N, P, and K, together with increasing rates of organic fertilizer originating from a biogas plant, increased the shoot growth of wheat grown in pots for 45 days up to 15% compared to plants supplied with only mineral N, P, and K (Erenoğlu and Hacirüstemoğlu, 2022). Consistent with these results, Tahir et al. (2011) and Shafi et al. (2020) stated that the application of humic substances boosted the agronomic responses of wheat under field conditions. However, Erenoğlu and Dündar (2020), in a short-term pot experiment (45 days) under greenhouse conditions, could not find any stimulating effect of humic substances on wheat growth. In a field trial conducted with wheat, in which compound fertilizers containing different NPs were compared, it was shown that although it was statistically not significant, 12.12.0+12S+OM fertilizer at a 250 $kg \cdot ha^{-1}$ rate resulted in more grain yield than the same rate of mineral fertilizer with 20.20.0+Zn content (Süzer and Çulhacı, 2017). Besides the combination of green manure yielded increased maize compared to the control (Mukuralinda et al., 2010). Moreover, the combined application of inorganic fertilizer and organic amendment might be a suitable approach for sustainable production systems under no-tillage which potentially causes hardening in the soil. For example, under such conditions, applying vermicompost with inorganic fertilizer enhanced stover and grain yields in sweet corn (Canatoy and Daquiado, 2021).

### *The Effect of OMF-P on P, N, and K Uptake of Wheat*

Some of the well-known characteristics of P are high fixation, slow diffusion, and low availability, making P one of the major limiting factors for average plant growth in arid climates (Shen et al., 2011). As shown in *Figure 1*, the presence or addition of humic substances can effectively increase the availability of P in the soil (Xing et al., 2020; Farid et al., 2021). In addition, although organomineral fertilizers are effective only in the root zone of a plant, known as the rhizosphere, and not the entire soil in a field due to their low application rates, this can result in better root development. Thus, it may also increase the use efficiency of nutrients, especially for those with limited mobility, such as P. These improvements in root development, together with the advances in the mobility of elements such as P, can positively affect the growth of plants. Similarly, adding humic acids from vermicompost to the growth medium of pepper (Arancon et al., 2006), banana, strawberry, and cowpea (Quility and Cattel, 2011) increased root mass. The combined effect of increased P availability in soil and root growth can lead to improved P uptake, increased plant growth, and enhanced nutrient utilization efficiencies.

Although it provides a meagre organic matter contribution to the soil compared to directly applied animal manure compost, the organomineral P application, especially at practical P application rate (25 $mg \; P \cdot kg^{-1}$) has also led to increased P uptake (*Figures 4A* and *B*; *Figures 6B* and *C*), as in plant growth (*Figure 2*; *Figures 3A* and *B*). At the end of


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the tillering period, the plants supplied with OMF-P had higher shoot P concentration and P uptake per pot than MF-P-applied plants. It became more pronounced as the application rate decreased and approached the P rates in the field. At 25 mg $P \cdot kg^{-1}$ rate, OMF-P applied plants showed 28% and 44% more P concentration and P uptake in the first harvest than MF-P used ones (*Figures 4A* and *B*). These results are also consistent with the research of Erenoğlu and Hacırüstemoğlu (2022), which showed that organic fertilizer and N, P, and K application increased both P concentration and uptake compared to mineral N, P, and K applications. Regarding harvesting at maturity, although the P concentrations in the grains of OMF-P treated plants are slightly higher than those of MF-P treated plants, they are statistically insignificant (*Figure 5B*). However, when the total P uptakes are evaluated, it is seen that the P uptake of OMF-P-treated plants is higher than that of MF-P-treated plants (*Figure 6C*). In this manner, at the lowest P rate, the grain P content and total P uptake of OMF-P applied plants were 19.7 and 13.6% higher, respectively, than those of MF-P used. While these differences were statistically insignificant at higher P rates, the difference was statistically significant at the lowest P rate (as in the practical applications) (*Figure 6C*). Similarly, under irrigated conditions, OMF-P application increases the P uptake in wheat compared to MF-P applied plants (Erenoğlu et al., manuscript in preparation). In fact, in the OMF-P application at 40 kg $P \cdot ha^{-1}$ rate, wheat plants have similar total P uptake as those plants treated with MF-P at 120 kg $P \cdot ha^{-1}$ rate. Accordingly, the combined application of animal manure with half-reduced inorganic P fertilizer (DAP) increased the P concentration in the shoot of chickpeas (Khan et al., 2022). In line with this, under no-till conditions, parallel to yield increases in sweet corn grown with complete NPK and vermicompost, vermicompost application boosted total N, P, and K uptakes. Recently, it has been shown that DAP fertilizer coated with humic acid increases P availability in soil, photosynthesis activity, and yield of maize (Chen et al., 2021). In addition, it has been found that while the coated-DAP fertilizer increases the efficiency of P use by 8.4% compared to the non-coated, this application also produces economically profitable results.

In contrast to the P, the OMF-P application did not stimulate either the concentration (*Tables 2* and *3*) or the uptake (*Tables 2* and *4*) of N and K compared to MF-P. However, in a recent study by Erenoğlu and Hacırüstemoğlu (2022), it was shown that although the application of N, P, and K with organic fertilizer did not cause an increase in N and K concentrations compared to those with mineral N, P, and K, it increased the total uptake of the plant.

## Conclusions

In summary, the conclusions drawn from the results of the present study are presented as follows:

- OMF-P application increases the availability of P in the experimental calcareous soil in comparison to MF-P.
- Organomineral fertilizers produced using an organic fertilizer containing and originating from a biogas facility may positively affect plant growth and yield.
- In addition, at P rates close to the application rates under field conditions, the total P uptake and the P accumulation in grains of OMF-P-supplied wheat plants were higher than that of MF-P-used plants.


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However, the results of the current study must be compared with the data obtained from future experiments that will be carried out under field conditions, and the actual effects of the OMF-P application should be revealed.

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